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An Automated Design Framework for Assembly Task Simulation

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Abstract

This paper presents an automated design framework for the development of individual part forming tools for a composite stiffener. The framework uses parametrically developed design geometries for both the part and its layup tool. The framework has been developed with a functioning user interface where part / tool combinations are passed to a virtual environment for utility based assessment of their features and assemblability characteristics. The work demonstrates clear benefits in process design methods with conventional design timelines reduced from hours and days to minutes and seconds. The methods developed here were able to produce a digital mock up of a component with its associated layup tool in less than 3 minutes. The virtual environment presenting the design to the designer for interactive assembly planning was generated in 20 seconds. Challenges still exist in determining the level of reality required to provide an effective learning environment in the virtual world. Full representation of physical phenomena such as gravity, part clashes and the representation of standard build functions require further work to represent real physical phenomena more accurately.

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1. Introduction

Digital methods such as computer aided design (CAD), finite element analysis (FEA), computational fluid dynamics (CFD) and product lifecycle management (PLM) have now matured to the extent that they have become ubiquitous across all engineering design disciplines. Multidisciplinary interaction has also become routine as interface methods and codes have been developed which allow the seamless interchange of data between platforms and disciplines for the purpose of developing optimal engineering systems. Opportunities still exist to enhance and exploit automated design methods through better use of tacit design knowledge

in concept development and broader use of virtual methods for design evaluation as a product and its manufacturing requirements evolve. If these opportunities can be exploited then OEMs would be in a better position to overcome the perennial problems of time and cost overruns on major product development programs [1, 2].

Previous work has demonstrated the need for automated design methods and has shown how an aircraft fuselage section can be transformed from a simple 1D structural representation to a full blown 3D CAD model [3], see Figure 1. Methods have also been developed to develop assembly fixtures automatically based on rules derived from the geometric properties of the product itself [4], see Figure 2.

This work focuses on the development of an automated design framework for the development of tools suitable for forming a carbon fibre reinforced stiffener. In the context of this paper, automated design is defined as: *'the generation of 3D CAD geometry automatically through a custom coded user interface without direct designer interaction with the traditional CAD interface'*. Similar components differing only on key dimensions are used for the work. Part details, manufacturing procedures and tooling features are captured and embodied in the automated design code. The approach includes the use of the required geometrical relationships between the tool and part as well as the peripheral design rules required to form the tool geometry beyond the part / tool contact surfaces. These are used in turn to generate and articulate design options. The work includes the transfer of the resulting component and tool geometry to a VR environment enabling the virtual assessment of tooling functions. By providing an interactive and immersive human-computer interface this work creates an efficient framework for designing, planning and assessing composite part manufacture including tooling functionality with respect to the human user.

2. Method

2.1. Automated Design Framework

Figure 1 maps the framework used for the development of the composite layup tool required to form the stiffener. The process includes component inspection and definition of the data required to drive mould tool design.

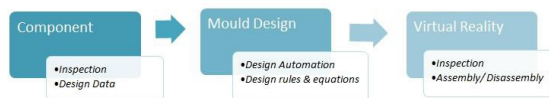


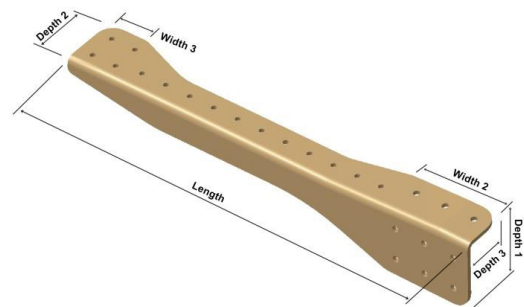
Fig. 1. Automated Design Framework for Virtual Development of Composite Layup Tool.

This was then used to develop tool forms based on critical features and dimensions as well as integrating the tacit knowledge of the tool designer i.e. 'in house' design rules and mould tool functions. These include the elements required for ease of handling by the user and how the tool integrates with the curing environment. The stiffener and its associated mould tool were then transferred to the virtual environment for functional assessment where the designer could interact with all elements of the system.

2.2. Structural Stiffener

Fig 2 shows the basic stiffener with the main dimensions highlighted. This component currently exists in two forms and the dimensions highlighted in Fig 2 vary for each case. Both versions of the stiffener have the same Thickness, Length, Width 1 and Width 2 (see Figure 2). All other dimensions differ for the two variants. The aim of this work was to create a third variant of the stiffener based on the design rules and key dimensions derived from the existing

components. During the inspection phase a subtle change in the profile shape along the surface defined by Widths 2 & 3 and Depths 2 & 3 was identified (see figure 3). A decreasing gradient along this surface meant that there was a variation between the two stiffener versions as the parts have to fit in



with different structural profiles during final assembly.

Fig. 2. Composite Stiffener.

2.3. Layup Tool

Fig 3 shows the composite layup tool with the main features highlighted, these are: The Mould Block which is a shelled feature with two underlying ribs, three holes required on upper surface as well as a further 18 holes for the periphery bar.

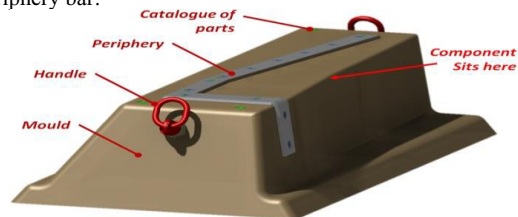


Fig. 3. Composite Layup Tool.

The Periphery Bar – which consists of three separate components and a total of 18 holes required for fixing component. Two Handles on the ends of the block and the Catalogue of Parts (Nuts, bolts and screws). The process for automated mould design started by assessing the features of the existing mould tools. This identified key features and dimensions. The moulds include multiple holes which vary in size, however despite the dimensional differences between the parts and mould for the two existing stiffeners, the hole properties on the tools remain identical for both.

The tool inspection process also included the comparison of the hole positions and part locations relative to a datum point located at the corner of the upper tool surface. See Figure 4. The mould tool also reflected the decreasing gradient along top surface of the stiffener. This feature is an important aspect of the layup tool as it forms a critical feature which interfaces with a higher profile on the aircraft. The automated development of this feature is critical to the overall success of the work as it influences assembly accuracy.

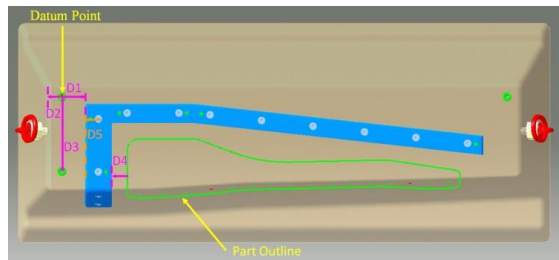


Fig. 4. Tool Inspection process: Definition of Positional Parameters for Automated design Process.

2.4. Computer Aided Design

Relating physical features to the CAD functions required to model them was a key element of this work. The key features on the tool were the part forming surfaces on the mould and the two end mounted handles. See Figure 3. Each of the primary physical features was sub-divided into the constituent parts (see Figure 5) and the next stage in the process required the translation of this feature data using a process that would enable the creation of the CAD models including the spatial relationships between features and parts. Once placed in the CAD environment the creation of repeated parts and features involved feature generation and copying functions. Axis systems were defined and used to control orientations and relative positions. This process formed the basis for a procedure which could automate the design of further components and tools differing only in key dimensions.

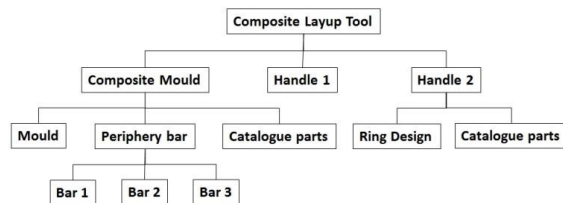


Fig. 5. Primary Geometric Elements for Composite Layup Tool.

Within the CAD environment the automated application of the modelling functions meant that some of the design components could be transferred from a parent part. This removed access to their design parameters and the system considered these as elements within a catalogue of standard parts. Although this meant that detailed design knowledge for these parts was limited, mapping out names and matching features was helpful when automating the design later in the process. This method was applied to the mould handles as well as the periphery bars. With all of the required design data gathered for both the stiffener and the mould tool, the process of automating the generation of further components could begin.

2.5. Automated Design

A user interface had previously been developed for the automated design of complex assemblies [5]. This

environment was re-used for this work (see Figure 6) and functionality was extended to include the design of the composite layup tool.

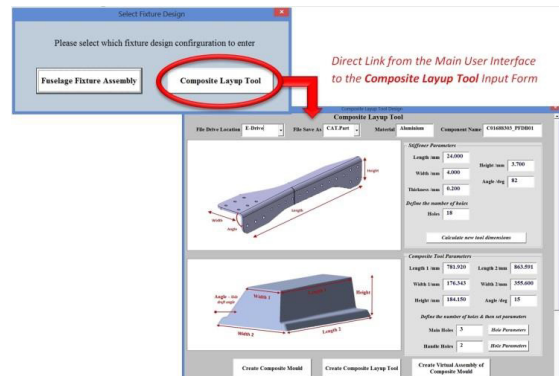


Fig. 6. User Interface For Automated Design of Composite Layup Tool For Aerospace Stiffener.

The interface is used only for the input of critical dimensions as required design variables. All knowledge, rules and mathematical functions are embodied and stored within the write protected VBA script. Lower level design parameters that are derived from the higher level component properties are also stored and accessed via the VBA script. An example is the size of the individual periphery bars which are based on the dimensions of the mould tool which is in turn, based on the size of the part. This pre-defined data structure helps to ensure the dimensional integrity of the components. If any changes are made to the high level component the low level parts are updated automatically, maintaining the design intent at all levels from the component through to the tool required to lay it up.

The user form can be broken down into three sections; non-design inputs, part design inputs & tool design inputs. The information on the forms is kept to a minimum and the user has just enough control to design the required component variant. Inputs required for repeated features come through the code – inputs required for the variable features come from the user via the interface. In addition to core design functions the interface includes file management capability for accessing, naming and saving documents and CAD files.

From the input of the stiffener parameters, the system can calculate the size of the composite layup tool based on the geometric information established during the analysis phases. These were subsequently combined with standard design practices and converted to the series of design rules used to derive the final tool geometry.

2.1. Virtual Reality

The virtual world is constructed using Python script for the VR software Vizard which can provide a fully immersive experience in a virtual environment. Unlike a typical CAD interface were geometry creation and manipulation functions are presented to the user in multi layered toolbars, VR platforms typically do not have a default user interface. All operations required when the user is in the environment must be coded to provide the user with the required functions when they are immersed. To achieve a realistic experience

interaction is based on the movement of the user which is based on the motion of their body and their inputs via a control device (A Nintendo Wii remote in this case). The user must be able to visualise and interact with the immersive environment. Immersion in and control of the VR environment can be achieved using a head mounted display (for stereoscopic visual immersion) and a motion tracking system which enables realistic body movement as sensors attached to the head and hand in this case, are tracked within a magnetic field (see Figure 7).

An example of the Python coding environment for VIZARD VR software is shown in Figure 8. A sample image of the resulting VR environment is also shown. The main aim of the VR system in the context of this work, was to create a realistic space that provided functionality for engineering processes. The environment used here was kept as simple as possible, and included a ground for walking on and a standard sky background. Two tables were used, one for placing containers on (with nuts, screws and bolts), and the other that accommodated the composite mould tool and the separated periphery bars. All of the components within the VR environment were taken from the CAD design concept developed using the automated design process described in earlier sections. All components were dis-assembled into a starting position in the virtual world so that the user could then assemble the mould tool.

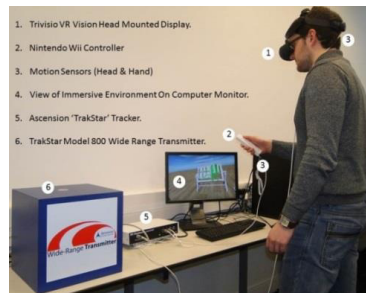


Fig. 7. Desktop Virtual Reality (VR) System.

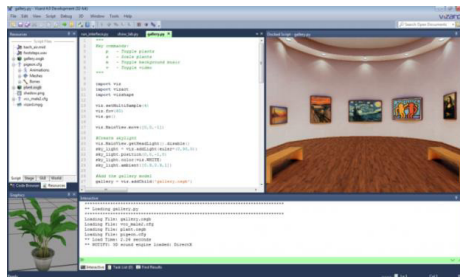


Fig. 8. Example of Python Coding Environment for VIZARD VR Software Including Sample Image of Resulting Environment. Ref. <http://www.est-kl.com>, Downloaded 30/1/16

3. Results

3.1. Creation of Composite Mould Tool Components

Figure 9 shows the pseudo code sequence or functions used for the creation of the composite layout tool in CATIA.

This embodied information related to the dimensional requirements of the tool (based on the stiffener sizes), the tool configuration (for features not in direct contact with the stiffener) and the basic CAD functions required to build the geometry.

The actual VBA code for the creation of an appropriate axis system (Item 3 on the pseudo code list in Fig 9) is listed in Figure 10. Equivalent functions were created for the other listed code elements which covered in sequence, all of the actions required to build the tool. A solid mould block for the main body was created first by extruding the required section. This was initially 'oversized' to allow material reduction as required to impart the required surface profiles on the mould tool which reflect the stiffener dimensions. This stage was listed as 'Create Split' in the pseudo code shown in Figure 9. It should be noted at this stage that the surface profiles used here were derived from existing tool geometries. These were manufactured taking into account material behaviours such as 'spring back'.

Create Composite Mould Tool:

1. Open CATIA
2. Create Absolute Axis
3. Create Tool Datum Axis
4. Create main Body
5. Copy Feature
6. Create Split
7. Create Base Plate
8. Create Edge Fillet
9. Create Shell Feature
10. Create Ribs
11. Create Holes
12. Create Final Edge Fillet
13. Final Save

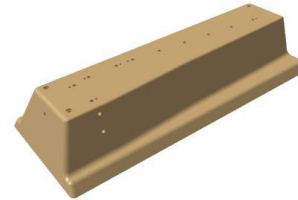


Fig. 9. Design Process Map for Functions Required to Create Composite Layout Tool.

```
Set PartDocument1 = CATIA.ActiveDocument 'Activates CATIA document
Set Part1 = PartDocument1.part
Set axisSystems1 = Part1.AxisSystems
Set axissystem1 = axisSystems1.Add()
axissystem1.Name = "Absolute Axis"
axissystem1.IsCurrent = 0
axissystem1.Type = 0
'Add new axis system
'Name new axis system
'Axis system is not current
'Axis system type set to standard
'Set origin co-ordinates for axis system
axissystem1.OriginType = 1
'Origin type is defined by co-ordinates
origincoord (0) = 0
origincoord (1) = 0
origincoord (2) = 0
axissystem1.PutOrigin origincoord
'Update axis system
Part1.UpdateObject axissystem1
```

Fig. 10. Code for 'Create Tool Datum Axis' Function.

The base plate was then added to the mould followed by the corner fillets. The geometry for these was governed by established design rules relating radius to material thickness. When the mould was formed as a solid block the 'shell' function was used to hollow it out to a standard thickness. Again this thickness was governed by standard practice.

Once the mould was shelled, two ribs were added to bridge the gap between the two long sides. These were required to add dimensional stability to the mould. The rib profile varied in accordance with sectional changes along the length of the mould but the process for creating both ribs was the same. The creation of hole positions to accommodate fasteners followed the required pattern relative to the model datum (see Figure 4). Individual hole sizes were specified according to the fastener type identified during the inspection stage. Smaller tooling elements including the periphery bar handles and individual fasteners were coded in a similar way to the main body of the mould. Again, each was saved as a CatPart file in preparation for final assembly as a CATproduct. The final coded element required for this process required the presentation of the user with save options. File extensions and locations were defined by the user through the user interface.

3.2 Assembly of Composite Mould Tool Components

The final stage in completing the composite layup tool involved the creation of a CATIA assembly (CATproduct) and the importation of the respective components (CATparts). All of the individual parts were required for this stage and the system only needed to read in their final position to create the final tool assembly.

The process for opening and saving a CATIA Product document is identical to that used during the creation of the individual mould pieces, however in coding terms, instead of 'Add(("Part"))' the system adds a product, 'Add(("Product"))'. The challenge in this area of the system was in how the parts were added and fitted together to form the final product. Parts must be constrained and fixed relative to one another in order to create a valid assembly within CATIA. In this case the mould is the primary component within the assembly and the additional parts were positioned relative to it using (x, y, z) positional and rotational coordinates.

3.3 Assembly Analysis Using Virtual Reality (VR)

The first step required in the construction of a virtual space for assembly analysis was to convert the CAD files to the wrl format required for the virtual world within VIZARD. This was offered as a file save option in the user interface of the automated design tool. Figure 11 shows the composite layup tool after the CAD data was migrated to the virtual environment. The 'GrabHand' script shown in Figure 11 was used for grabbing objects with physical effects included (i.e. gravity & component clash). In addition to the 'geometry import' and 'position set' functions, physics and grabbing functions were also included, in the virtual environmental settings. The grab function is clearly required to enable the user to lift and place objects in the assembly. The physics function is required to improve the sense of reality within the system where parts clash if they come in to contact and pieces fall due to the forces of gravity if they are dropped. To achieve this, collision shapes have been added to all of the objects in the environment. An additional sound function helps the user to understand when a collision has occurred.

With the above functions established the user was then free to lift and place individual pieces into their 'as designed' positions. This enabled the completion of an assembly based, virtual assessment of the mould design concept where the automated tools compressed the time from concept development to virtual assembly from days / weeks to a matter of minutes. The process produced a CAD design for the composite mould tool in less than 3 minutes and created a virtual environment to interact with the design in 20 seconds.

```
grabObjects = [Bar1, bar2, Bar3] #List of objects to grab
#Pass in the list of hands to the physics engine for processing
Import GrabHand
Grabhand.GrabHandList (grabObjects,
Handlist=viztracker.getHandlist (), springs=True)
```

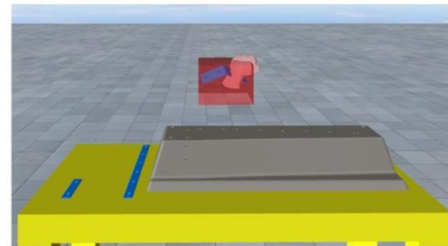


Fig. 11. Python Script For 'Grab & Move' Function Within Vizard VR Environment.

4. Discussion

The aim of this work was to link an automated design framework with a virtual reality environment. The intention was to create capability which allowed the user to carry out design/assembly analysis with shorter lead times using automatic design and virtual assembly tools that will allow the production of better quality systems and products as the manufacturing systems are designed concurrently with the products. The knowledge acquired from the CAD documents has been utilised to assemble a set of automated codes for the purpose of developing conceptual tool designs in the virtual environment.

The work was able to successfully create an automated design process to develop a composite layup tool based on the design of the part that it will form (structural stiffener). It also showed how a direct link with the virtual world can be created to inspect, assemble and disassemble the new design concept. The process was able to produce a CAD design in less than 3 minutes and create a virtual environment with that design in 20seconds. The approach presented in this paper will have maximum impact to parts or families of parts, with common features because the time required to generate the automated code will only be offset if a single, core code can be applied repeatedly. If the design process follows basic principles in design associated with best practice in design for manufacture and assembly (DFMA) then the lead time benefits demonstrated by this work are eminently possible. Although the work focused on a composite layup tool as single design application, the outcomes are equally applicable to any structural element manufactured using a forming tool.

Concurrent engineering (CE) systems and practices have focused on the integration and alignment between design and manufacturing; this has already proven to reduce manufacturing costs and improve product quality [5]. The use of CE in the redesign of the Airbus A340 resulted in an estimated reduction of 25% in development time and 30% product costs [6]. The success of any integrated design environment is dependent on individuals sharing information and collaborating during the decision making process. True concurrency is difficult to achieve. For the work completed for this paper the product geometry must exist before the tool required to form it, can be considered. However, the system presented here begins to approach concurrency when the process from part concept through tool design to virtual build validation is reduced to minutes rather than days. The consideration of multiple options through iterative loops in very short time periods means that tool development is for all intents and purposes concurrent.

The learning and innovative capability of an organisation is critically dependent on its capacity to mobilise tacit knowledge and foster its interaction with explicit knowledge [7]. Establishing a framework to organise and capture this knowledge such as the one presented here, will not only preserve the knowledge it also avoids any associated loss or waste and means that it can be used repeatedly and consistently. Accurate knowledge presentation and visualization also enables organisations to explore knowledge spaces so as to gain better understanding and insight [8].

Researchers have suggested that virtual environments could provide advantages for conceptual learning by allowing opportunities for learners to view information within the context of meaningful locations [9]. This work provides a means by which this can be achieved even at the conceptual development stage as the automated tools can place the operator in a virtual environment to gain familiarity with the manufacturing setup before prototypes or physical systems are produced. Organizational learning involves gaining experience with products and processes, achieving greater efficiency through automation and other capital investments, and making other improvements in administrative methods or personnel. Unfortunately, the core dilemma that confronts all organisations is that they learn best from experience but they never directly experience the consequences of many of their most important decisions [10]. VR capability provides a means by which the experiential elements of the learning process can now be gained before production begins. When coupled with automated design capability, the time required to create and use the VR environment is offset by significantly reduced design lead time. The time (and therefore cost) based benefits of the approach presented here are supplemented by the potential for achieving 'right first time' production systems that have been validated in the virtual world. The improved learning environment will also benefit operator learning reducing the likelihood of errors when production begins. This has been observed by other authors including Mujber [11].

Future manifestations of the methods presented in this paper will require development of the core design methods to include intelligent codes. These will integrate 'as manufactured' part form predictions within the design code to avoid the need for referencing / inspecting existing hardware to understand phenomena such as spring back. Further work and investment is also required to accurately determine, capture and exploit knowledge behind the design process to an extent where the automated design methods presented here can move beyond single components to span entire systems. Although this work presents the mechanism for placing the designer in front of his creations in a virtual environment, further work is required to quantify the learning benefits of this approach.

By combining parametric design methods with improved exploitation of tacit knowledge, the potential to improve the design system generally, produce better quality products with more efficient manufacturing systems thereby reducing development lead times, becomes a reality.

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